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Progress in Horizontal and Slant-Path Imaging Using Specking Imaging

C.J. Carrano

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Progress in horizontal and slant-path imaging using speckle imaging

Carmen J. Carrano*
Lawrence Livermore National Laboratory, 7000 East Avenue, Livermore, CA 94550

ABSTRACT

The difficulty in terrestrial imaging over long horizontal or slant paths is that atmospheric aberrations and distortions reduce the resolution and contrast in images recorded at high resolution. This paper will describe the problem of horizontal-path imaging, briefly cover various methods for imaging over horizontal paths and then describe the speckle imaging method actively being pursued at LLNL. We will review some closer range (1-3 km range) imagery of people we have already published[1], as well as show new results of vehicles we have obtained over longer slant-range paths greater than 20 km.

Keywords: horizontal-path imaging, slant-path imaging, bispectral speckle imaging, extended scene reconstruction, long-range surveillance

1. INTRODUCTION

High-resolution imaging over long horizontal or slant paths is a problematic task due to atmospheric turbulence. If we want to recognize a person from a few kilometers, we need the resolution to be on the order of one centimeter or less, and if we want to identify vehicles from ten's of kilometers, we need the resolution to be on the order of 10's of centimeters or less. There are two primary effects caused by the fluctuations in the index of refraction in the atmosphere; one is image motion, and the other is image blurring. The scale of the atmospheric blurring is λ/r_0, where λ is the wavelength, and r_0 is the Fried atmospheric coherence length[2], typically 0.5 cm to 2 cm over horizontal or slant paths at visible wavelengths. The scale of the image motion depends on the mean gradient of the phase errors present in the incident wave at the telescope pupil and is inversely proportional to the telescope diameter[3].

2. APPROACHES TO IMAGE ENHANCEMENT

There are a number of approaches described in the literature on software methods for enhancing horizontal-path imagery. Some of these include the multiple shift and add (MSAA) method[4], image dewarping[5], measurement (e.g. phase) diversity[6], and multi-frame blind deconvolution methods[7]. In Ref. 1, we describe our sub-field speckle processing method in detail. The advantage of the MSAA and image dewarping methods is in the regime of total anisoplanatism when every point in the image has a different point spread function and the dominant image characteristic is local warping. We have performed a number of experiments in variable conditions and found that the sub-field speckle processing performs very well, even in cases where the isoplanatic angles appear to be very small, a few tens of pixels at most. At the point where speckle-processing alone breaks down due to severe anisoplanatism, which we have yet to observe experimentally, it is conceivable that dewarping could be a pre-processing step to the speckle processing. In the next sections we describe our image processing approach and show experimental results.

3. SUB-FIELD SPECKLE IMAGE PROCESSING

In Ref. 1 we describe the details and rationale of the sub-field image processing using bispectral speckle-imaging techniques. The primary processing steps are summarized in Figure 1. After obtaining the raw camera images, we mitigate artifacts from dust that may be on the camera CCD window by flat-fielding, which involves dividing each frame by a time average of reference flat-field frames. The frames are then registered to each other by applying shifts calculated from frame to frame cross-correlation. The large image data cube is next split up into sub-fields, which are overlapped by 50%. The sub-fields are then apodized and speckle processed. Finally, the processed tiles are reassembled to form the full sized image.

* E-mail: carrano2@llnl.gov

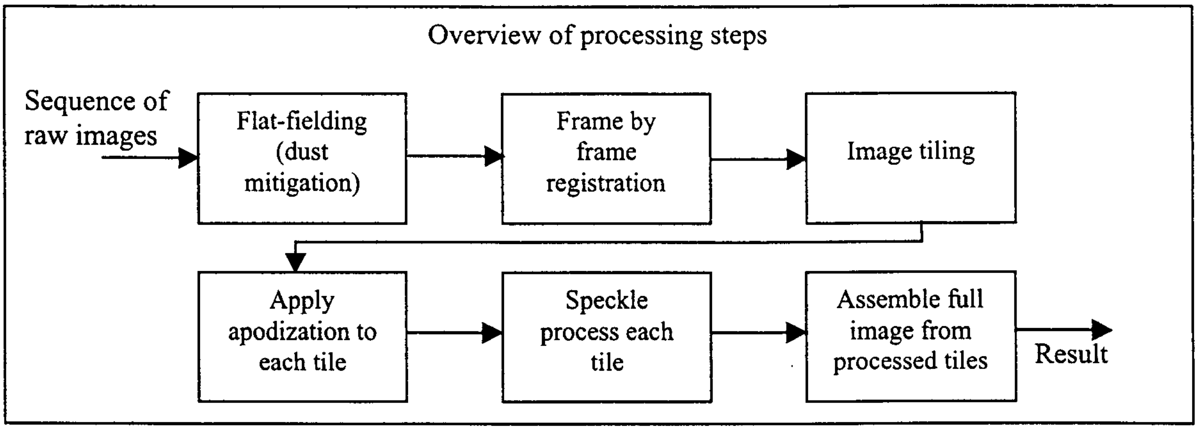


Figure 1: Block diagram overview of processing steps for producing enhanced images of extended scene, horizontal path imagery via speckle processing.

4. EXPERIMENTAL DESCRIPTION AND RESULTS

4.1 Equipment

Our prototype speckle imaging system consists of the following equipment:

Telescope:	Celestron 8-inch or 11-inch diameter Schmidt-Cassegrain, f/10
Camera:	Qimaging Retiga 1300, 12-bit CCD camera, 1280 by 1024 pixels, 6.7 by 6.7 μm pixel size, Readout noise level of 8 e-, minimum exposure time 40 μs
Other Optics:	For close range used 3x Barlow lens to achieve Nyquist sampling
Computer:	PC laptop with IEEE1394 connection for data acquisition and image processing

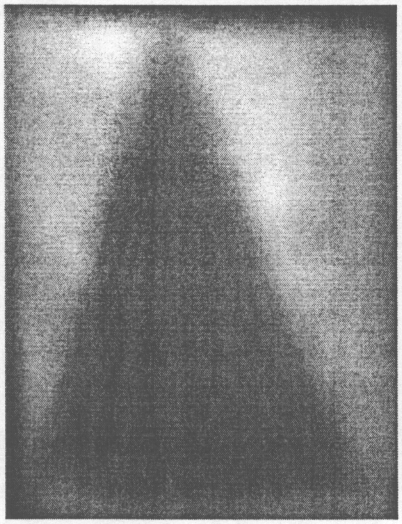
4.2 Experiments

Personnel experiments were performed from a hillside 500 feet above Mines road in Livermore looking out at various distances, 0.9, 1.3 and 3.3 km. And the long-range vehicle experiments were performed from the top of Mt. Diablo (3849') in California looking southeast at various ranges greater than 20km.

4.3 Previous results: resolution targets and personnel

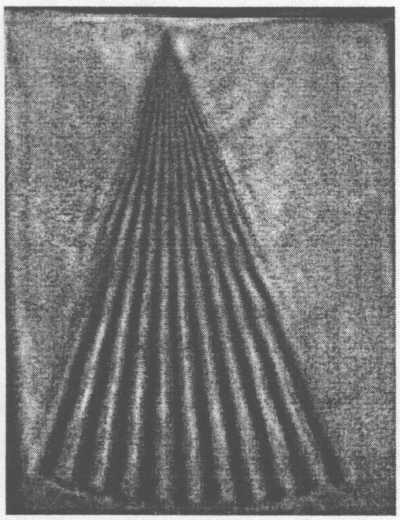
We now show highlights of results previously obtained. The first result, displayed in Figure 2 is that of a fan target acquired at 0.5 km range from a 2-story building rooftop. We show an example frame, a shift-and-add result, as well as the sub-field speckle processed result. The tile size used in this case was 512x512 pixels with 60% Hanning apodization, and r_0 was set to 1.25 cm. We are able to observe modulation nearly down to the diffraction limit of 1.4 mm.

The next few results were acquired from the low hillside telescope site. Figure 3 shows a raw frame, the shift-and-add result, and the speckle-tile processed result of a person standing at a 0.9 km distance. The processing parameters for this case were 256x256 sized tiles, 60% Hanning window apodization, and an r_0 of 2.0 cm. After speckle-tile processing, the image of the person is sharper and crisper, and in fact the person is now recognizable. The same observation holds true for the next result shown in Figure 4, which is the same person, but standing at 1.3 km distance. He is also holding a box with the word "MAGELLAN" on it whose letters are 1.6 cm tall, and clearly readable in the speckle-tile processed image. The next result is of two people and resolution targets at 3.3 km distance and is shown is Figure 5. In the speckle-tile processed image, small details about the people are more clearly visible as are the resolution targets.

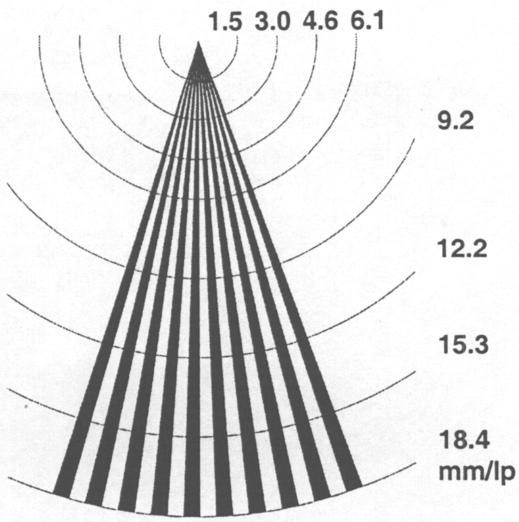


2a. Example frame

2b. Shift and add (50 frames)

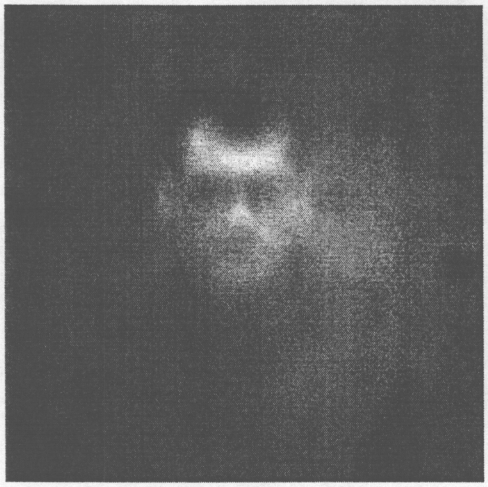


2c. Speckle-tile processed: 512x512 pixel sized tiles



2d. Ground truth for fan object

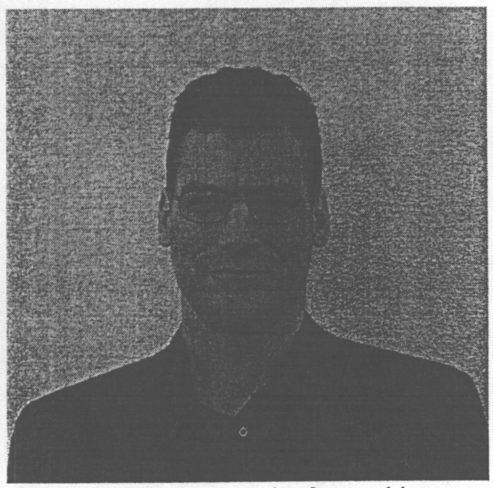
Figure 2: Results from fan target imaged at 0.5 km range with 5 ms exposure time on a hot summer day.



3a. Sample frame, dt = 10 ms

3b. Shift and add (100 frames)

3c. Speckle-tile processed: 256x256 sized tiles

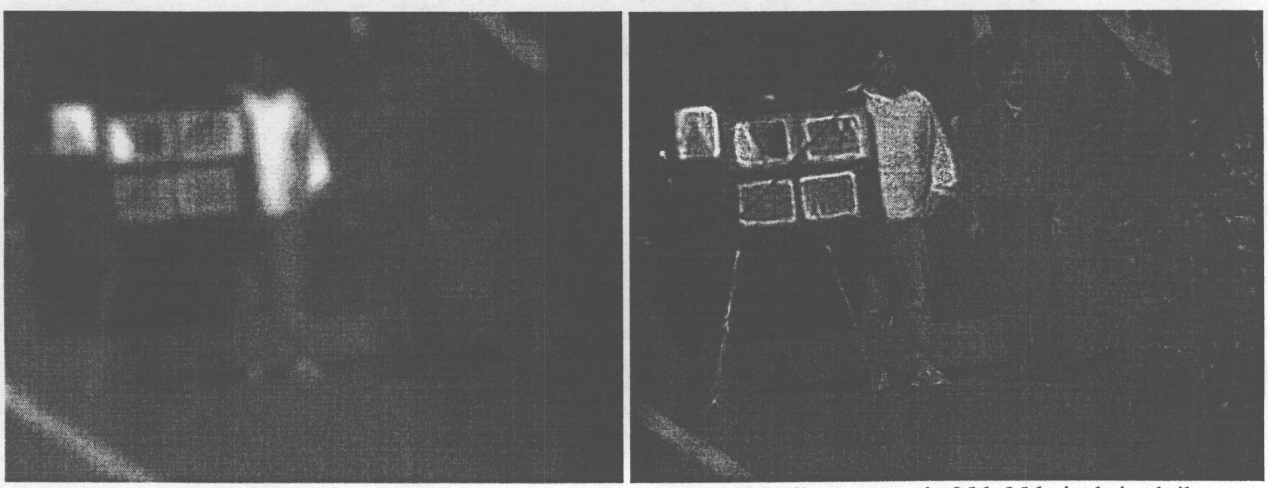


3d. Digital photograph of our subject

Figure 3: Results of a person imaged at 0.9 km distance on a cool winter morning.

4a. Shift and add (100 frames) 4b. Speckle tile processed: 256x256 pixel sized tiles

Figure 4. Results of person imaged at 1.3 km distance on a cool winter morning.



5a. Shift and add (100 frames) 5b. Speckle tile processed: 256x256 pixel sized tiles

Figure 5: Results of people and resolution targets imaged at 3.3 km distance on a warm breezy morning.

4.4 New results: vehicles

This next experiment was performed in order to determine experimentally if sub-field speckle imaging would be applicable in improving long slant-range surveillance images of vehicles. The imaging was performed from the top of Mt. Diablo, a 3849' peak located approximately 30 miles east of San Francisco. The location was selected to show surveillance examples from a high hillside vantage point as well as what could be expected from a low flying UAV. The imagery was obtained in November of this year. The weather was cool, and the visibility, hence the image contrast, was less than optimal due to a surface haze layer approximately 1000 feet thick. We staged the vehicle experiment with three different types of vehicles: a 20 foot long flatbed truck, a 24 foot long water truck, and a 23.5 foot long cargo van. These vehicles are shown in Figure 6. They were parked at three different ranges from the telescope, 22 km, 29 km, and 37 km. In all the cases shown, the Barlow lens was not used in order to have enough light for the short exposures. This means that we are slightly undersampled for fully reaching the telescope diffraction limit. It turns out that this did not matter, because the data is noise-limited beyond a frequency much lower (5-10x) than the diffraction limit.

The 22 km vehicle result is displayed in Figure 7. A sample frame is shown in Figure 7a and the speckle-tile processed result is shown in 7b. The r_0 used was 1.0 cm and 256x256 pixel sized tiles with 58% Hanning window apodization were used. The processed result clearly shows three distinct types of vehicles. The flatbed truck is identifiable as a flatbed. Also, the fence posts along the road and between the fields become clearly visible.

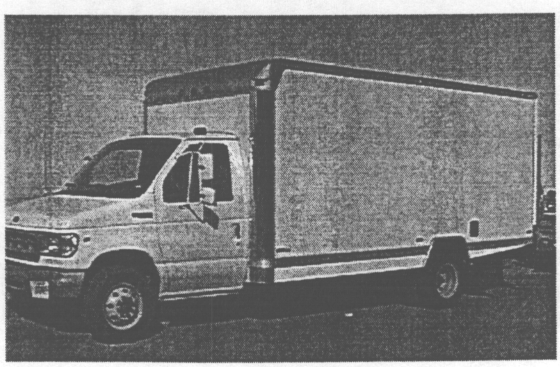
The 29 km vehicle result is shown in Figure 8, with a sample frame in Figure 8a, and the processed result in 8b. Notice that the sun angle with respect to the vehicles has changed. They are being illuminated from the side rather than from behind as in the previous case. The r_0 used was 1.5 cm and 256x256 pixel sized tiles with 58% Hanning window apodization were used. The objects in the processed image exhibit crisper edges and even the wheel wells on the large cargo truck (to the right) is visible.

The furthest vehicle result at a range of 37 km is displayed in Figure 9. Again the r_0 used was 1.0 cm and 256x256 pixel sized tiles with 58% Hanning window apodization were used. In the sample frame, it is not obvious what we are looking at, but in the processed image, we can see that there are three vehicles on what appears to be a road. Likewise, the foliage looks much sharper and crisper in the processed image.

The final result shown in Figure 10 is not of vehicles, but rather of Lick Observatory as seen from Mt. Diablo. The range is approximately 40 miles (64 km). The r_0 used was 2.0 cm, which is better than in the previous imagery. This is probably attributable to the imaging path, which is at least 3000 feet above the ground most of the way, except at the two endpoints. Likewise, the Observatory sat above the haze layer, so the contrast of the raw imagery was better. The processed image is very impressive in that it shows the details of the windows in the buildings as well as the surrounding trees and foliage.

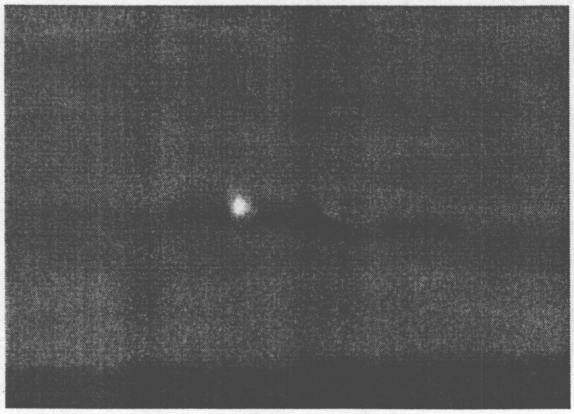
6a. Flatbed truck

6b. Water truck

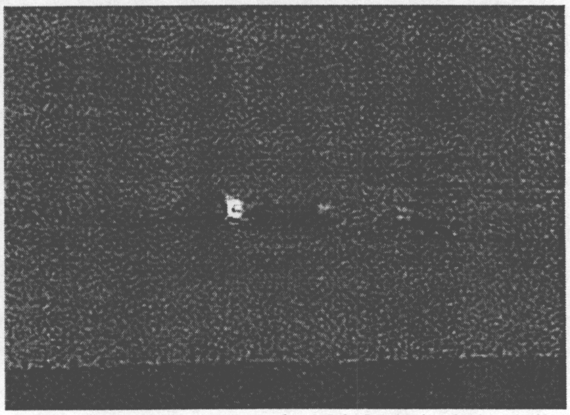


6c. Cargo truck

Figure 6: Photographs of the trucks used in the vehicle experiments.

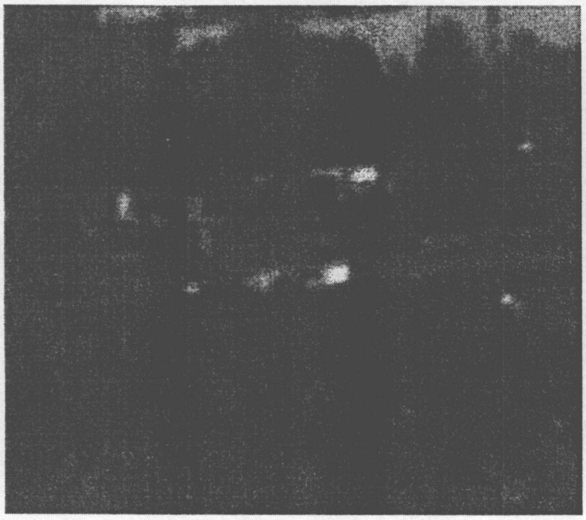


7a. Sample frame, dt = 0.9ms

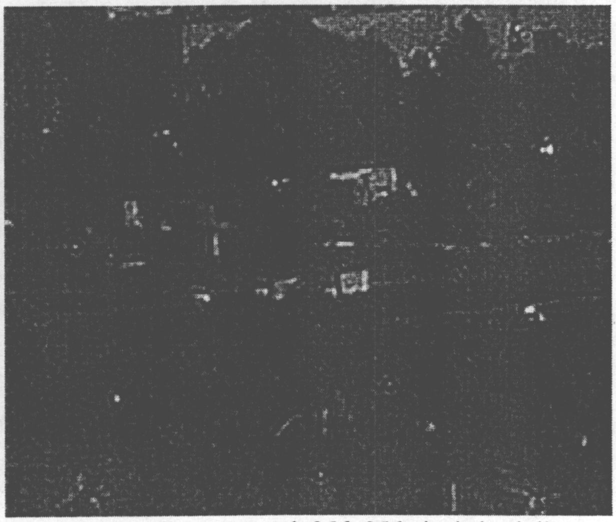


7b. Speckle-tile processed: 256x256 pixel sized tiles

Figure 7: Three trucks from 22 km range. The left most vehicle is the cargo van, the center vehicle is the water truck, and the right most vehicle is the flatbed truck.



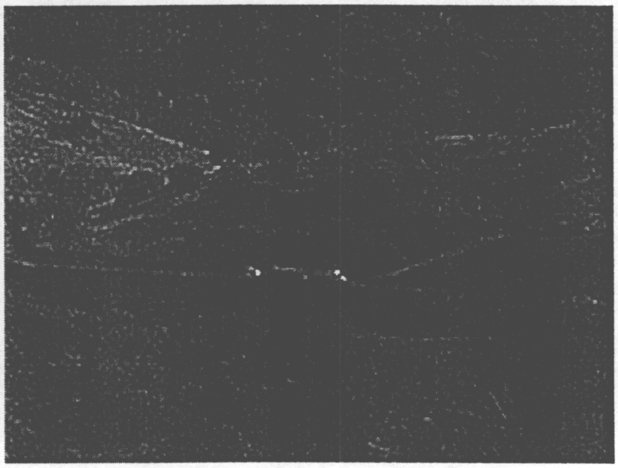
8a. Sample frame, dt = 2.0 ms



8b. Speckle-tile processed: 256x256 pixel sized tiles

Figure 8: Three trucks from 29 km range. The left most vehicle is the flatbed truck, the center vehicle is the water truck, and the right most vehicle is the cargo van.

8a. Sample frame, dt = 1 ms



8b. Speckle tile processed: 256x256 pixel sized tiles

Figure 8: Same three trucks at 37 km range. The left most vehicle is the flatbed truck, the center vehicle is the water truck, and the right most vehicle is the cargo van.

9a. Sample frame, dt = 1 ms

9b. Speckle-tile processed: 256x256 pixel sized tiles

Figure 9: Lick Observatory as seen from Mt. Diablo, 64 km range.

5. CONCLUSIONS

We have experimentally demonstrated the usefulness of sub-field speckle processing to near and far range slant-path surveillance imaging. These speckle imaging techniques can make personnel recognizable from a few km and vehicles more recognizable at 10's of km. This surveillance technology could be fielded from a number of platforms (eg. hillside, tower, UAV) for a number of surveillance purposes (eg. personnel and vehicle identification.) We are currently working on speeding up the software and implementing it on an appropriate computing platform so that this capability could be fielded in a real-time imaging situation. We are also investigating extensions to low light level situations such as with night-vision.

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